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Optimizing Resin Sealant Microhardness: The Impact of Curing Distance, Time, and Light-Curing Mode

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ABSTRACT

Background: Effective polymerization of resin-based pit and fissure sealants is essential for their clinical success and longevity. One of the most widely used indirect indicators of polymerization efficiency is microhardness, which reflects the material's mechanical integrity and degree of monomer conversion. **Objectives:** The current research evaluated the effect of varying irradiance intensities, exposure times, and curing distances using a multi-emission peak Light Emitting Diode (LED) curing device on the microhardness of a resin-based sealant.

Materials and methods: A total of ninety disc-formed samples were constructed utilizing an opaque mold using light-curingopaque-filled sealant (UltraSeal XT plus).The specimens were split into 18 groups (n = 5) based on curing distances (2 mm, 4 mm, and 6 mm), three curing modes [Standard (1000 mW/cm²), High-Power Plus (1400 mW/cm²), and Xtra-Power (3200 mW/cm²)], and two curing durations per mode. Knoop microhardness testing was performedon every sample's top and bottom surfaces.

Results: All main effects (curing setting, distance, and curing period) were statistically significant for both top and bottom surfaces. The extended curing times and reduced distances generally produced higher microhardness values. Notably, while higher irradiance levels improved bottom surface microhardness in some configurations, inconsistent performance was observed at higher intensities over shorter durations. The Standard mode with extended curing time consistently produced superior top surface microhardness.

Conclusions: The microhardness of resin-based sealants was significantly affectedby curing distance, curingperiod, and the light-curing mode. The extended exposure times and reduced distance improve surface and bottom microhardness.

Keywords: Resin-based sealants; Knoop Microhardness; Curing distance; Irradiation time; light intensity.

INTRODUCTION

Resin-based pit and fissure sealants are a necessary component in preventive dental field, particularly in the management of occlusal surfaces that are highly susceptible to caries. The complicated morphology of pits and fissures on molars and premolars creates an environment conducive to the accumulation of food debris and bacterial biofilm, making them difficult to clean effectively with routine oral hygiene practices(1). Consequently, sealing these areas with resin-based materials produces a substantialobstruction that inhibits the penetration of cariogenic agents and helps to maintain enamel integrity. Sealants are especially effective in children and adolescents, where the caries risk is significantly heightened as the permanent teeth are erupting (2).

Among the properties critical to the long-term clinical success of resin-based sealants are their mechanical performance and resistance to degradation. One of the most widely adopted indirect measures for evaluating these attributes is microhardness, which serves as a proxy for the degree of conversion (DC) of resin monomers into a cross-linked polymer matrix. Higher microhardness values typically indicate better polymerization, improved wear resistance, and enhanced longevity of the sealant(3). Conversely, insufficient polymerization can result in softer resin matrices that are vulnerable to hydrolytic degradation and leaching of residual monomers, thereby compromising the material's performance and potentially its biocompatibility(4).

Despite the light curing technological advancements, there remain considerable variability in clinical outcomes due to differences in curing protocols. It is often assumed that higher irradiance levels lead to better curing; however, recent evidence suggests that the relationship is more nuanced(5). Extremely high irradiance over very short durations may not allow sufficient time for complete polymer chain formation, potentially resulting in suboptimal mechanical properties(6). Moreover, the distance amongst the light curing device and the resinous material surface can significantly attenuate the delivered light energy, further complicating the curing process. As such, understanding how these variables interact to influence microhardness is critical for optimizing clinical protocols(7). As the pit and fissure sealants cannot be light-cured at a distance below three millimeters because the depth of the pits and fissures varies from 1 to 3 mm, and the cusps can exceed 3 mm (8).

Microhardness testing, particularly using the Knoop Hardness Test, provides a simple yet informative method for evaluating the surface integrity of resin composites. Unlike Vickers hardness, the Knoop test creates an elongated indentation that is more sensitive to surface irregularities, making it especially suitable for thin materials like sealants(9). Knoop microhardness values have been displayed to be related strongly tothe degree of conversion, particularly for the top surfaces exposed directly to the curing light(10). However, this correlation tends to diminish for the bottom surfaces, where light attenuation can lead to insufficient polymerization. Therefore, measuring both top and bottom surface microhardness is essential for a comprehensive evaluation of curing efficacy(11).

The objectives of the current research were directed to analyze the effects of different curing parameters involving three light curing deviceapproaches (Standard, High Power Plus, and Xtra Power), three curing distances (2 mm, 4 mm, 6 mm), and two exposure times per mode (short and extended) to the microhardness of a resin-based sealant. The null hypothesis of the current research was that there would be no significant variation in the microhardness of resin-based sealants cured under different irradiance intensities, exposure durations, or curing distances using a multi-emission peak LED light-curing unit.

MATERIALS AND METHODS

Materials

The resin-based sealant used in this study was an opaque-filled sealant (UltraSeal XT plus, Ultradent, South Jordan, UT, USA). This material includes diurethane dimethacrylate (<10%), BisGMA (<20%), 2-dimethylaminoethyl methacrylate (<1%), Fluoride: sodium monofluorophosphate (<1%), Opaquer: titanium dioxide (<1%), Fillers: (58%), and ethyl p-dimethylaminobenzoate as a Photoinitiator. The sealant is designed for light activation and is commonly used in preventive dentistry for sealing pits and fissures on coronal tooth surfaces.

The light curing unit (LCU) employed was a VALO LED LCU (Ultradent, South Jordan, Utah, USA). This unit features a polywave light source capable of emitting in a spectral range from 385 to 515 nm, encompassing the absorption spectra of both camphorquinone and alternative photoinitiators. The device was assessed in three operational curing approaches:

1. Standard Mode (S): 1000 mW/cm²
2. High Power Plus Mode (H): 1400 mW/cm²
3. Xtra Power Mode (X): 3200 mW/cm²

These curing modes reflect the irradiance output, allowing for assessment of performance under varying energy conditions.

Sample Size Calculation

According to priorresearch by Alrahlah et al. (2014) (12). The sample size determination was made utilizing G power test analysis,which recorded that: a sample size of 5 specimens per group was determined adequate to detect an effect size of 2.0, with 80% statistical power and a two-sided significance level of 5%, accordingto a two-sample t-test calculation. This ensured sufficient sensitivity for detecting meaningful differences in microhardness between test groups.

Preparing the Samples

A total of ninety disc-formedsamples have been fabricated utilizing an opaque polytetrafluoroethylene (PTFE) mold with dimensions of 6 mm in diameter and 1 mm in thickness. The mold was positioned on a glass slide previously covered with a celluloid strip to ensure a uniform and smooth base surface. The mold was filled with sealantby the injection and covered with a celluloid strip to ensure a uniform surface as well as avoidthe development of the oxygen-inhibited layer. A glass slide was positioned over the strip to exert slight pressure and eliminate air entrapment during polymerization.

The specimens (n=90) were divided into 18 groups (n = 5 per group) based on combinations of three curing distances (2 mm, 4 mm, and 6 mm), three curing modes (S, H, and X), and two curing durations per mode. Each curing mode was evaluated using two exposure durations based on the manufacturer's recommendations: a short curing period and a prolongedcuring period time. Specifically, the Standard mode was applied for 10 seconds (short) and 30 seconds (extended), the High-Power Plus mode for 8 seconds (short) and 20 seconds (extended), and the Xtra Power mode for 3 seconds (short) and 9 seconds (extended).

Each curing distance was measured between the specimen's surface and the LCU light guide's tip. For standardization, a Managing Accurate Resin Curing System – Resin Calibrator (MARC-RC, Blue Light Analytics, Halifax, Canada) had beenutilized. This system ensured precise positioning and perpendicular alignment of the LCU tip to the specimen surface for consistent energy delivery.

After polymerization, the composite samples were carefully extracted from the mold **(Figure 2)** and kept in sealed containers lined with water-moistened paper towels to maintain 100% relative humidity. These containers were placed in an incubator at 37°C for 24 hours to ensure completion of any post-cure polymerization reactions.

Light Irradiation and Calibration

Before each test session, irradiance was verified using the MARC-RC's built-in 4-mm diameter sensors. This calibration ensured consistency of light output throughout the testing process. The LCU tip (9.6 mm diameter) was aligned directly over the specimen using the mechanical arm of the MARC-RC. The testing environment was maintained at an ambient temperature of 22°C ± 1°C and a relative humidity of 24% ± 5% under orange ambient lighting to prevent premature light exposure.

Microhardness Testing (Knoop Microhardness Test)

The microhardness was evaluatedutilizing a Leco LM247AT microhardness tester (MI, USA) equipped with Confident V 2.5.2 software. The test employed a diamond indenter with a load of 25 grams and a dwell time of 10 seconds. Five non-overlapping marks were produced on each surface (top and bottom) of every sample, which were situated at the center, top, bottom, left, and right quadrants, ensuring a 1 mm spacing between indents and 2 mm from specimen edges. Mold markings facilitated consistent positioning across all specimens. Meanmicrohardness values were calculated per surface for statistical analysis.

Statistical Analysis

A three-way Analysis of Variance (ANOVA) was performed to assess the effects of curing mode, curing distance, and exposure time on microhardness outcomes. The model involved both two-way and three-way interactions. Where necessary, a logarithmic transformation of data was applied to correct for non-normal distribution. Pairwise comparisons between groups were made using Fisher's Protected Least Significant Difference (LSD) post hoc test. A p-value of less than 0.05 was deemed statistically significant. SAS version 9.4 (SAS Institute Inc., Cary, NC, USA) was used for all statistical analyses.

RESULTS

Our results revealed that the three-way ANOVA confirmed that all main effects—curing approach, distance, and curing period—were statistically significant ($p < 0.05$) for both top and bottom microhardness values. Interaction effects across mode and time, as well as distance and time, were also significant.

Top Surface Microhardness

Top surface microhardness values showed substantial variation across curing parameters. In the Standard mode, extended curing durations produced higher microhardness across all distances. The highest top surface microhardness was observed in the S6-30 group (51.17 ± 20.30), followed by S2-30 (31.09 ± 6.59). In contrast, S6-10 recorded the lowest microhardness in this mode (12.85 ± 2.32).

In the High-Power Plus mode, results were less consistent. The H4-20 group achieved a top microhardness of (32.57 ± 7.75), surpassing its shorter duration counterpart and some Standard mode groups. However, H2-8 (15.02 ± 5.15) and H6-8 (15.02 ± 2.72) yielded relatively low values.

The Xtra Power mode, characterized by the highest irradiance, resulted in notably low top surface microhardness values when used with short curing periods. X2-3, X4-3, and X6-3 groups recorded values of (5.85 ± 1.78, 5.49 ± 1.49, and 4.58 ± 0.24), respectively. Despite using an irradiance of 3200 mW/cm², the brief exposure appeared insufficient to adequately harden the sealant surface. Slight improvements were observed with extended exposure: X2-9 reached (33.29 ± 10.62), while X4-9 and X6-9 recorded (21.49 ± 12.56 and 21.26 ± 5.67), respectively. Data is summarized in **Table (1)and Figure (1)**.

Bottom Surface Microhardness

As expected, bottom surface microhardness values were generally lower than their corresponding top surface values, reflecting the diminished light intensity reaching the lower layers of the material. The highest bottom MICROHARDNESS was observed in S2-30 (28.22 ± 7.71). S4-30 and S6-30 followed with values of (19.97 ± 2.34 and 13.98 ± 2.79), respectively.

In the High-Power Plus mode, the bottom microhardness ranged from (4.57 ± 2.72) in H6-8 to (25.42 ± 7.72) in H4-20. Interestingly, H4-20 and H6-20 showed superior performance compared to their Standard counterparts.

The Xtra Power mode presented mixed outcomes. Short exposure groups again produced the lowest values: X6-3 and X4-3 showed (5.02 ± 0.44 and 5.22 ± 0.47), respectively. However, under extended exposure, bottom microhardness values improved: X2-9 recorded (27.81 ± 5.78), comparable to S2-30, while X4-9 and X6-9 showed moderate improvements at (21.29 ± 1.96 and 16.41 ± 2.37), respectively. Data is summarized in **Table (2)and Figure (2)**.

Top vs Bottom Comparisons

There were significant variations (*) between the top and bottom surfaces across most curing configurations. These disparities were most pronounced under short curing times. Under extended curing, some combinations (e.g., High Power Plus at 6 mm and Xtra Power at 4 mm) achieved near parity between top and bottom surface microhardness, suggesting more uniform polymerization when both exposure time and mode parameters are optimized. Data is summarized in **Table (3) and Figure (3)**.

Table 1. The microhardness scores for the resin-based sealants' top surfaces after being cured by every light curing approach at various intervals and distances

	Standard			**High Power Plus**			**Xtra Power**		
Distance	2 mm	4 mm	6 mm	2 mm	4 mm	6 mm	2 mm	4 mm	6 mm
Short Time	24.49 ± 7.62^{bc*}	25.77 ± 5.88^{bc*}	12.85 ± 2.32^{d*}	15.02 ± 5.15$^{d*\wedge}$	21.25 ± 6.72$^{c\wedge}$	15.02 ± 2.72$^{d\wedge}$	5.85 ± 1.78$^{e*\wedge}$	5.49 ± 1.49$^{e*\wedge}$	4.58 ± 0.24$^{e*\wedge}$
Extended Time	31.09 ± 6.59^{b*}	15.37 ± 5.19^{d*}	51.17 ± 20.30^{a*}	21.05 ± 4.71$^{c*\wedge}$	32.57 ± 7.75^{b*}	24.49 ± 7.62^{bc*}	33.29 ± 10.62$^{b\wedge}$	21.49 ± 12.56^{c}	21.26 ± 5.67^{c*}

Table 2. The microhardness scores for the resin-based sealants' bottom surfaces after being cured by every light curing approach at various intervals and distances

	Standard			**High Power Plus**			**Xtra Power**		
Distance	2 mm	4 mm	6 mm	2 mm	4 mm	6 mm	2 mm	4 mm	6 mm
Short Time	9.13 ± 1.74^{c*}	18.01 ± 5.88^{b*}	5.49 ± 0.47^{c*}	13.37 ± 5.15$^{bc*\wedge}$	8.69 ± 6.72$^{c*\wedge}$	4.57 ± 2.72^{c*}	6.01 ± 2.30$^{c\wedge}$	5.22 ± 0.47$^{c*\wedge}$	5.02 ± 0.44^{c}
Extended Time	28.22 ± 7.71^{a*}	19.97 ± 2.34^{b*}	13.98 ± 2.79^{bc*}	17.89 ± 4.71$^{b\wedge}$	25.42 ± 7.72^{a*}	24.89 ± 3.48$^{b*\wedge}$	27.81 ± 5.78$^{a\wedge}$	21.29 ± 1.96^{b}	16.41 ± 2.37$^{bc\wedge}$

Lowercase superscripts (a, b, c, d, e): Significant differences within each LCU mode row
Asterisks (*): Significant differences between LCU modes at the same curing condition
Carets (^): Column-wise significant differences (same distance and time) across modes

Table 3. The comparison of top versus bottom surface microhardness scores (short and extended curing periods)

	Standard			**High Power Plus**			**Xtra Power**		
Distance	2 mm	4 mm	6 mm	2 mm	4 mm	6 mm	2 mm	4 mm	6 mm
Top Short	$24.49 \pm 7.62^{bc*}$	$25.77 \pm 5.88^{bc*}$	$12.85 \pm 2.32^{d*}$	$15.02 \pm 5.15^{d*\wedge}$	$21.25 \pm 6.72^{c\wedge}$	$15.02 \pm 2.72^{d\wedge}$	$5.85 \pm 1.78^{e*\wedge}$	$5.49 \pm 1.49^{e*\wedge}$	$4.58 \pm 0.24^{e*\wedge}$
Top Extended	$31.09 \pm 6.59^{b*}$	$15.37 \pm 5.19^{d*}$	$51.17 \pm 20.30^{a*}$	$21.05 \pm 4.71^{c*\wedge}$	$32.57 \pm 7.75^{b*}$	$24.49 \pm 7.62^{bc*}$	$33.29 \pm 10.62^{b\wedge}$	21.49 ± 12.56^{c}	$21.26 \pm 5.67^{c*}$
Bottom Short	$9.13 \pm 1.74^{c*}$	$18.01 \pm 5.88^{b*}$	$5.49 \pm 0.47^{c*}$	$13.37 \pm 5.15^{bc*\wedge}$	$8.69 \pm 6.72^{c*\wedge}$	$4.57 \pm 2.72^{c*}$	$6.01 \pm 2.30^{c\wedge}$	$5.22 \pm 0.47^{c*\wedge}$	5.02 ± 0.44^{c}
Bottom Extended	$28.22 \pm 7.71^{b*}$	$19.97 \pm 2.34^{b*}$	$13.98 \pm 2.79^{c*}$	$17.89 \pm 4.71^{c\wedge}$	$25.42 \pm 7.72^{b*}$	$24.89 \pm 3.48^{b*\wedge}$	$27.81 \pm 5.78^{b\wedge}$	21.29 ± 1.96^{b}	$16.41 \pm 2.37^{c\wedge}$

Lowercase superscripts (a, b, c, d, e): Significant differences within each row (i.e., within each time and surface group)
Asterisks (*): Statistically significant variationsacross the top and bottom surfaces at the same curing mode and distance
Carets (^): Statistically significant differences within a column (same curing distance and time across curing modes)

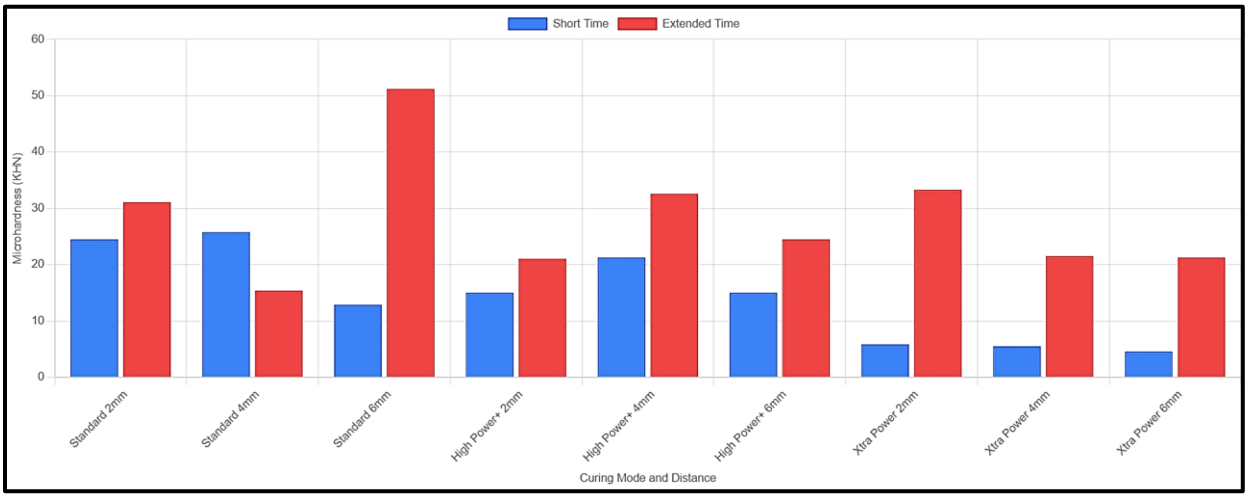

Figure 1: Bar chart representing the microhardness scores for the resin-based sealants' top surfaces after being cured by every light curing approach at various intervals and distances

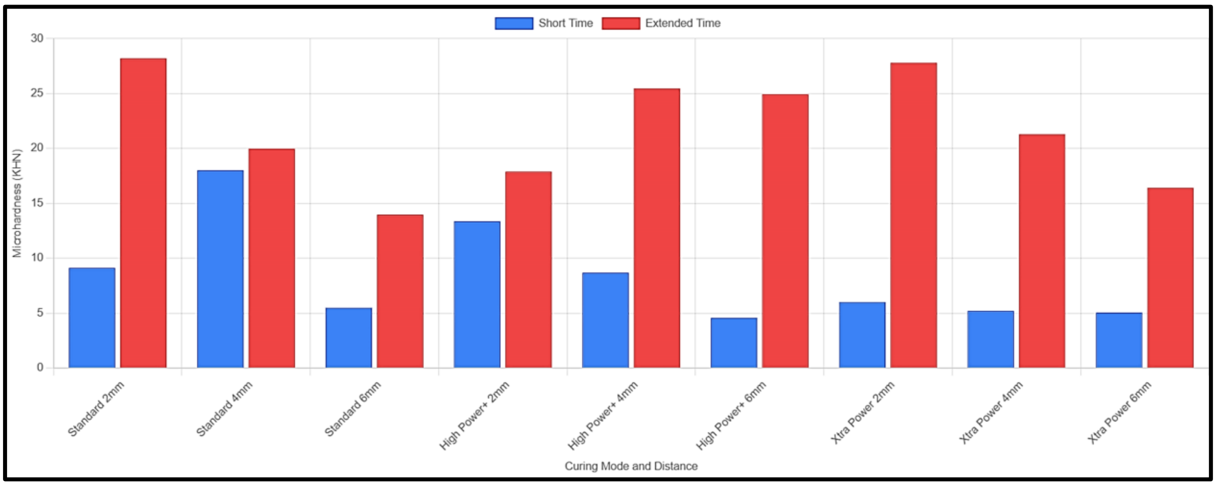

Figure 2: Bar chart representing the microhardness scores for the resin-based sealants' bottom surfaces after being cured by every light curing approach at various intervals and distances

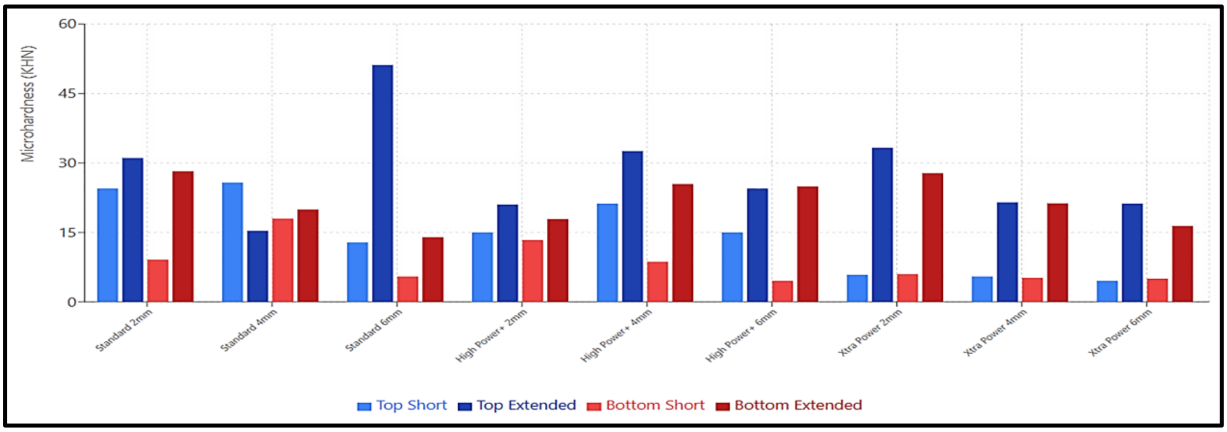

Figure 3: Bar chart representing the comparison of top versus bottom surface microhardness scores (short and extended curing periods)

DISCUSSION

Light-cured resin sealants are the most commonly used and conventional type of sealant. The efficacy of resin-based sealant polymerization has been assessed using a variety of techniques. Among them, several studies have employed the microhardness test to evaluate the efficacy of illumination and indirectly measure the polymerization of resin-based sealants[1,3,4]. Moreover, A material's degree of conversion can be inferred indirectly from its microhardness. Measuring the top and bottom surfaces of a sample yields valuable information on the degree of polymerization (curing) [16].

Though little is known about the many versions of LED curing systems [17]. It is commonly recognized that adequate radiant exposure at the proper photoinitiator light wavelengths is necessary for the successful light-curing of a resin-based sealant[18]. However, because each design uses different optical properties, the spectrum radiant power obtained from LED curing devices differs significantly [19]. Thus, it is also necessary to look at how characteristics of resin-based sealants are affected by elements associated with LED curing devices.

The substances utilized to seal dental fissures in a clinical setting typically possess a thickness of 1 mm[20]. The light source of the curing device could be positioned at varying distances from the sealant surface throughout occlusal sealing, like 3 mm, according to the dimensions of the cusp and the shape of the pits and fissures. This will increase the dispersion and reduce the intensity of the light that reaches the sealant [8]. Consequently, to replicate clinical circumstances, thespecimen's thickness and distance have to be taken into account throughout sample processing.The present study investigated the effect of varying light-curing modes, exposure durations, and curing distances on the microhardness of resin-based sealants, as measured by the Knoop microhardness test.

Our results demonstrated a significant decrease in microhardness values with increasing curing distances. Specifically, specimens cured at 6 mm exhibited notably lower microhardness values compared to those cured at 2 mm, regardless of the light-curing mode employed. This was consistent with previous studies that have reported diminished light intensity and, consequently, reduced polymerization efficiency with increased distance amongst the light source and the resinous material surface [11,25].When the distance between the light source and the sealant increases, the intensity of the light reaching the sealant decreases. This means less energy is available to initiate and complete the curing progression(polymerization),and when the distance amongst the light source and the resin-sealant rises, the effective polymerization depth decreases[21].

The fundamental principle of light propagation, the Inverse Square Law, dictates that the intensity of light from a point source diminishes proportionally to the square of the distance from the source. Consequently, doubling the distance reduces the light intensity to one-fourth of its original value. While this law is widely cited, some studies suggest that its strict adherence may not be observed across all clinical distances due to the complex nature of LCU light sources. Nevertheless, the general trend of decreasing intensity with increasing distance is consistently reported[22].

Besides, filler particles within the resin matrix of the tested resin sealant may induce significant light scattering, which reduces light transmission and its effectiveness with increasing depth into the material[23].Additionally, photoinitiators and pigments within the resin absorb specific wavelengths of light, further contributing to the reduction in light intensity with depth. The material's inherent color, opacity, and filler content play a crucial role in the extent of this internal attenuation[24].

Additionally, our results displayed that prolonged exposure times were associated with increased microhardness values, particularly at greater curing distances. For instance, extending the curing time from 10 seconds to 30 seconds at a 6 mm distance resulted in a substantial improvement in microhardness values. This observation aligns with the principles of the exposure reciprocity law, which posits that the total energy delivered (product of light intensity and exposure period) dictates the level of curing. Studies have corroborated that longer curing durations can compensate for reduced light intensity, thereby enhancing the mechanical characteristics of the polymerized resinous material(25).According to Peutzfeldt et al.(26), the longer photopolymerization times had the most impact on the microhardness of resin composite; shorter curing durations led to lower microhardness scores.

Furthermore, the present outcomesfound that the combination of longer curing time and reduced distance enhances bottom surface polymerization.Indeed, by extending the exposure time, more photons are delivered over time, allowing for greater absorption and a higher degree of polymerization to be achieved (27). Experimental evidence demonstrates that prolonged exposure times can significantly enhance the microhardness at the bottom surface and improve the microhardness bottom-to-top ratio of resin-based materials. This effect is particularly pronounced when curing is performed at greater distances from the light curing device tip or when suboptimal light intensities are employed(28). Our results agreed with those of Kim et al. (29) who found that the extended curing time led to an increasein the bottom microhardness of the resin-based sealants.

Among the light-curing approaches evaluated, the Xtra Power mode, despite its higher intensity, did not consistently yield superior microhardness values, especially at increased curing distances. This counterintuitive finding may be attributed to the rapid polymerization induced by high-intensity light, which can lead to increased polymerization shrinkage and internal stresses, potentially compromising the integrity of the resin matrix (6). Despite the high initial irradiance of Xtra Power mode, the fundamental principles of light attenuation (inverse square law, scattering, and absorption within the material) still apply. At greater distances, even a high-power mode will experience a significant reduction in the effective light intensity reaching the sealant material(30).Peutzfeldt and Asmussen (31) observed that the degree of polymerization reduced as power density increased for every single energy density, indicating that resin composite qualities were significantly influenced by both energy density and power density in general.

Conversely, our results revealed that the Standard and High-Power Plus modes, when combined with extended exposure times, achieved more uniform and higher microhardness values across varying distances. This can be attributed to the cumulative energy delivered to the resin composite during polymerization. This cumulative energy is a product of the light intensity and the period of curing, commonly referred to as energy density (J/cm^2) (32). The outcomes of the currentresearch reject the null hypothesis. Statistically significant variations were observed in microhardness values based on curing mode, curing distance, and exposure time.

A consistent observation across all experimental conditions was the greater microhardness scores at the top surfaces compared to the bottom surfaces of the resin specimens. This disparity is expected due to the attenuation of light as it penetrates deeper into the resin, resulting in reduced energy availability for polymerization at the bottom layers(33). Gjorgievska et al. (34) found that Light attenuation prevents the deeper layers from achieving optimum curing (polymerization).

When the lightcuring device is applied to the surface of the resinousmaterial, the top layer receives the highest intensity of light, facilitating optimal activation of photoinitiators and resulting in increased polymerization level(35). As light travels through the composite, it undergoes scattering and absorption, resulting in a decrease in light intensity with increasing depth. This reduction in light intensity leads to a reduction in the polymerization level of monomers to polymers at the bottom surface, thereby resulting in decreased microhardness values (36).

The limitations of the current research were the in vitro setting of the experiments,which may not fully replicate clinical conditions, where factors such as oral fluids, temperature variations, and patient movement can influence curing outcomes. Additionally, only one type of resin sealant was used.Future studies ought to focus on validatingourresults in clinical settings and exploring the long-term performance of different resin sealants cured under varying protocols.

CONCLUSIONS

The microhardness of resin-based sealants is significantly affected by curing distance, curing period, and the specific light-curing mode. While extended exposure times enhanced surface polymerization, even at increased curing distances, a detrimental effect was observed with both increased distance and reduced exposure time. Conversely, the combination of longer curing time and reduced distance enhances bottom surface polymerization, and moderate increases in irradiance may benefit deeper resin layers when combined with appropriate exposure time.

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